Thin Fuel Film Reactor Testing for Characterization of Diesel Fuel Deposit Formation

by

Orian Welling

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

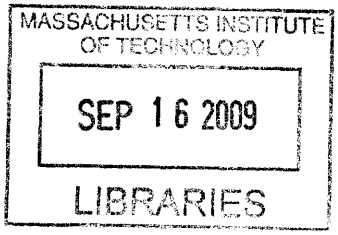
at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2009

© Orian Welling, MMIX. All rights reserved.

The author hereby grants to MIT permission to reproduce and distribute publicly paper and electronic copies of this thesis document in whole or in part.



Author .....
Department of Mechanical Engineering
December 18, 2008

Certified by .....
Wai Cheng
Professor
Thesis Supervisor

Accepted by .....
John H. Lienhard V
Professor of Mechannical Engineering
Chairman, Undergraduate Thesis Committee

ARCHIVES

Thin Fuel Film Reactor Testing for Characterization of Diesel Fuel Deposit Formation

by

Orian Welling

Submitted to the Department of Mechanical Engineering
on December 18, 2008, in partial fulfillment of the
requirements for the degree of
Bachelor of Science in Mechanical Engineering

Abstract

The need for specialized diesel fuel injectors is growing with increased efficiency and emissions regulation. These specialized fuel injectors have nozzle diameters of 150-200μm which are susceptible to clogging from deposit formation. This thesis studies the deposit formation mechanisms with a thin fuel film reactor, and examines the potential for use of the reactor as a detergent screening tool.

Through experimentation with the thin fuel film reactor it was found that temperature had negligible effect on the weight of a fully dried fuel film. This suggests that testing could be conducted at high or low temperatures to decrease the cycle time or increase test resolution respectively. It was also determined that dry deposits remain soluble in hot fuel immediately following drying, but become insoluble after long hot soak periods.

A simple deposit formation model was constructed based on hypothesized formation factors. Although very simplified, the model matched the experimental results well. The correlation suggest that the hypothesized formation factors are critical to the formation process. The model should be expanded to explain deposit formation more generally, and further research should be conducted to better validate the model.

Thesis Supervisor: Wai Cheng
Title: Professor

Contents

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 1

Introduction

Increasingly stringent efficiency and emissions laws have driven manufacturers of diesel vehicles to develop highly specialized diesel fuel injectors driven at very high pressure ($\sim 2000bar$). The nozzle diameter is reduced accordingly to provide fuel metering resolution and to achieve good atomization and spray pattern. Current nozzle diameter is in the 150-200μm range. As injector nozzle diameters have decreased, diesel engines have become increasingly susceptible to malfunctioning associated with deposit buildup in the nozzles. Although there has been significant development of fuel detergents to reduce deposit formation, the mechanisms by which these deposits form are complex and are still not well understood. Development of these diesel fuel detergents relies heavily on empirical data from engine testing. The high cost and long times needed for engine testing pose a significant challenge to rapid development of new detergents. This thesis studies the deposit formation mechanisms with a thin fuel film reactor, and examines the potential for use of the reactor as a detergent screening tool.

1.1 Deposit Formation Mechanisms

Research investigating the formation of deposits from fuels and lubricants suggests that oxidation of hydrocarbons is the primary mechanism by which deposits form. However, the chemical and physical pathways of this process are not well understood.

While oxidation chemistry has been studied for some components of fuels (especially alkanes), there are many other components that have not been studied. The large number and varieties of chemical species present in fuels make comprehensive kinetics modeling difficult. In addition, the chemical reactions are occurring in a dynamic environment with flushing of the nozzle content by the fuel and rapid changes in temperature and pressure. Finally, metallic components such as zinc compounds have been shown to significantly increase the rate of deposit buildup [8], but it is not know if the zinc acts as a catalyst or reacts to form an integral part of the deposit [1] [3] [2].

The thin film fuel reactor presented in this thesis was developed in collaboration with an MIT group investigating deposit formation mechanisms and the behavior of diesel fuel detergents. The group has proposed a simple explanation for the mechanism by which deposits form in diesel fuel injector nozzles from oxidation of high molecular weight components in diesel fuel. Three primary steps contribute to the deposit formation mechanism as shown in Figure 1-1. First oxygen diffuses into the film and reacts with the hydrocarbon molecules (through autoxidation) to form deposit precursors. Although the oxygen reacts with hydrocarbons of various molecular weights, the concurrent evaporation of low molecular weight components leaves an increasing concentration of high molecular weight components in the fuel which become oxidized and eventually make up the bulk of the deposit. A second oxidation step continues as the precursors grow in size (polymerization) and increase in concentration as more liquid fuel evaporates. Eventually the concentration of precursors becomes sufficiently high to start the third step, in which the precursors condense and adhere to the substrate.

The deposit buildup mechanism proposed by the MIT group is similar to one proposed by research by Kinoshita et. al. [7] which lead to a similar theory for deposit buildup in fuel injection nozzles in direct injection gasoline engines. Analysis of deposits formed at 260 °C with jet fuel by Venkataraman and Eser [10] found that the deposits consisted primarily of oxidized hydrocarbons while nitrogen and sulfur remained suspended in the fuel until the next injection cycle washed them away. This

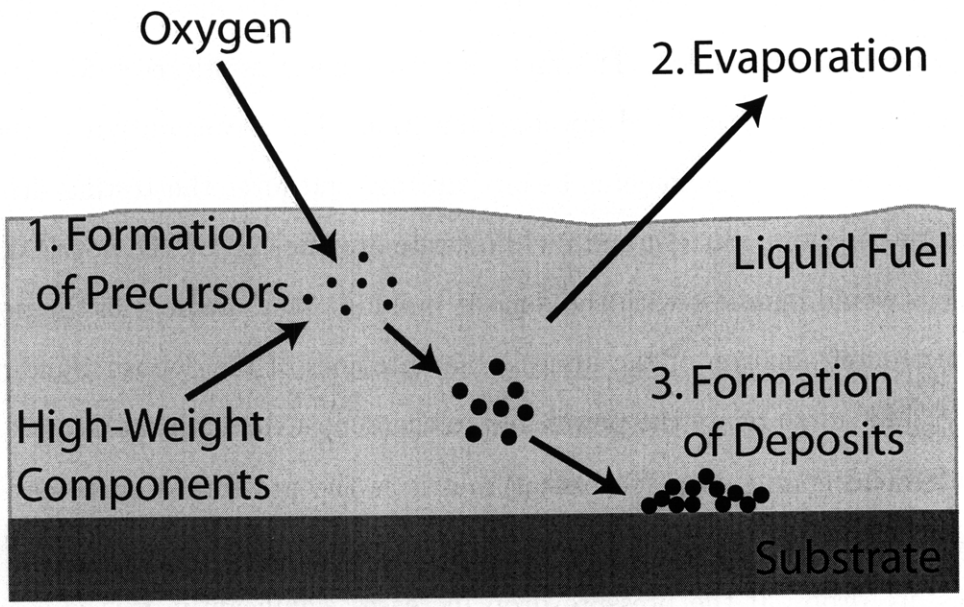


Figure 1-1: Mechanism of Deposit Buildup. Oxygen diffuses into the fuel layer and reacts with hydrocarbon to form deposit precursors. Concurrent evaporation of low molecular weight components helps drive the increase in concentration of precursors from high molecular weight components. The concentration of precursors becomes sufficiently high to cause condensation and adherence to the substrate.

is further evidence that at least in this temperature range the deposits are primarily formed through oxidation of the fuel.

It is hypothesized that the role of a fuel detergent is for it to bind to the deposit precursors which would then remain soluble in the non polar fluid. The fuel from the next injection cycle will wash the residual fluid away. Thus engine shutdown could be a primary process for deposit buildup. The fuel in the injector nozzle when the engine is shut off will experience a hot-soak period which will likely be long enough for deposits to form before the engine completely cools and the remaining fuel is washed away on the next start up.

1.2 Engine Testing

Several standard engine testing procedures have been established to determine the quality of fuel detergents [1] [11]. These engine tests generally consist of an engine

which is connected to a dynamometer and run through a pre-determined drive cycle. There are several metrics by which the quality of the diesel fuel detergent can be quantified in these tests. The first and most basic metric is power loss in the engine when operating at fixed injection duration. The power output of the engine is measured at the dynamometer before, during, and after the testing drive cycle. Because the injection pattern and fuel flow rate are affected by the nozzle deposit, a power loss would manifest with the deposit buildup. Measurement of the power loss is a direct determination of the undesirable outcomes of the deposit buildup. It is, however, difficult to relate the power loss to the deposit buildup rate.

The second common engine testing metric is the pressure drop across the fuel injector. The engine is stopped and fuel is flowed through the nozzles to determine the pressure drop. If the pressure drop increases significantly, this is a sign that buildups have partially occluded the nozzles.

Although engine testing is very time consuming and costly it is unlikely it will be fully replaced any time soon. Detergents and other fuel additives can have important effects on the performance of the engine; they may have secondary effects unrelated to the problems they are designed to solve. One example is the increase in Zn concentration in fuel with acid based fuel detergents. The zinc presence increases the deposit buildup rate [4]. The Zn is believed to be absorbed by the fuel from fuel system components in the vehicle when acid based detergents are used instead of ester based detergents. Engines and the chemical reactions which take place inside them, are sufficiently complex that it is important to run these types of engine tests just to make sure that no adverse effects were overlooked.

1.3 Screen Testing Methods

While engine testing should ultimately be conducted for a detergent before it goes to market, these tests are costly and time intensive and limit the ability of detergent developers to test a wide variety of potential detergents in order to narrow in on the best choice. A low cost screening method can be used to first check a new detergents

response to a system where most of the important factors in deposit buildup are present while other engine systems are eliminated.

Some low cost screening tests have been developed in the past [6] [9], but these tests have still rely on some form of engine testing. Although the simplified engines and running cycle used in these screening tests allow the test to be completed in as little as 6 hours, only one fuel can be tested at a time and a new injector must be used for every test. A thin film reactor screen testing method attempts to mimic only the most important parameters involved in deposit formation. The thin film reactor testing method would allow many fuels to be tested at once, require no injectors or engines, and would uses only a small amount of each test fuel.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 2

Thin Fuel Film Reactor

The thin film fuel reactor was designed to capture the most significant factors leading to deposit formation while at the same time remaining simple enough to easily extract some information about the deposit formation mechanisms. The resulting design is not meant to fully replace more complex testing methods such as engine testing, but is significantly less expensive and faster than these more complicated testing procedures and may provide useful information about contributions of individual factors to the deposit buildup.

2.1 Design Criteria

2.1.1 Capturing Critical Factors

The thin fuel film reactor was designed to take into account the factors thought to be most important to diesel fuel deposit formation while eliminating factors which only have a secondary effect. The deposits are believed to form from oxidation and polymerization of the high molecular weight components of the fuel to form deposit precursors. As the fuel evaporates and more precursors form the concentration of precursors eventually becomes high enough for the deposit to form. At the conception of this project it was believed that a significant amount of the deposit formation occurred during the long hot-soak period after engine shut off since the fuel in the

injector nozzle remains heated for a long period of time in which it can also interact with the air at its free surface.

Evaporation

Evaporation is an important factor in deposit formation. Once the fuel has evaporated, it no longer can form a deposit on the injector nozzles. However, as fuel evaporates the concentration of the precursors in the nozzle increases. Evaporation rates are dependent on many factors including temperature, density, and air flow. The thin, wide films used in the thin film fuel reactor help to control this variable to some degree during the experiment by maintaining a nearly uniform surface area through the testing.

Oxidation

Oxidation of the fuel to form precursors requires oxygen to either be present in the fuel or to diffuse into the fuel to react. Though diffusion rates vary with temperature, the thin film has a large surface area to interact with the environment but a small thickness for the oxygen to diffuse across. in the thin fuel film geometry, the effects of diffusion become less important and attempts can be made to measure more fundamental properties.

Deposit Formation

Once the concentration of precursors is high enough, they will begin to condense to form deposits. A thin fuel film decreases the required diffusion distance for a precursor to move from the fuel surface to the substrate, and the reaction rate is most likely only limited by the condensation kinetics.

2.1.2 Practicality of Testing Apparatus

In addition to capturing the important parameters responsible for diesel deposit buildup while eliminating as many secondary parameters as possible, it was also

required to design a testing system that could be scaled easily and was easy to use. Although the test setup was only implemented with 10 sample holders as shown in Figure 2-1, attempts were made to keep scale up of the design straightforward. The test consists of a heated surface with temperature control and disposable sample holders that constrain the fuel film. The sample holders were held in place on the heated surface with bolts to increase the contact force and thus improve heat transfer to keep the sample as close to the temperature of the plate as possible. A hotplate with digital temperature control was used for the heated surface of the prototype testing system. Sample holder design was more involved.

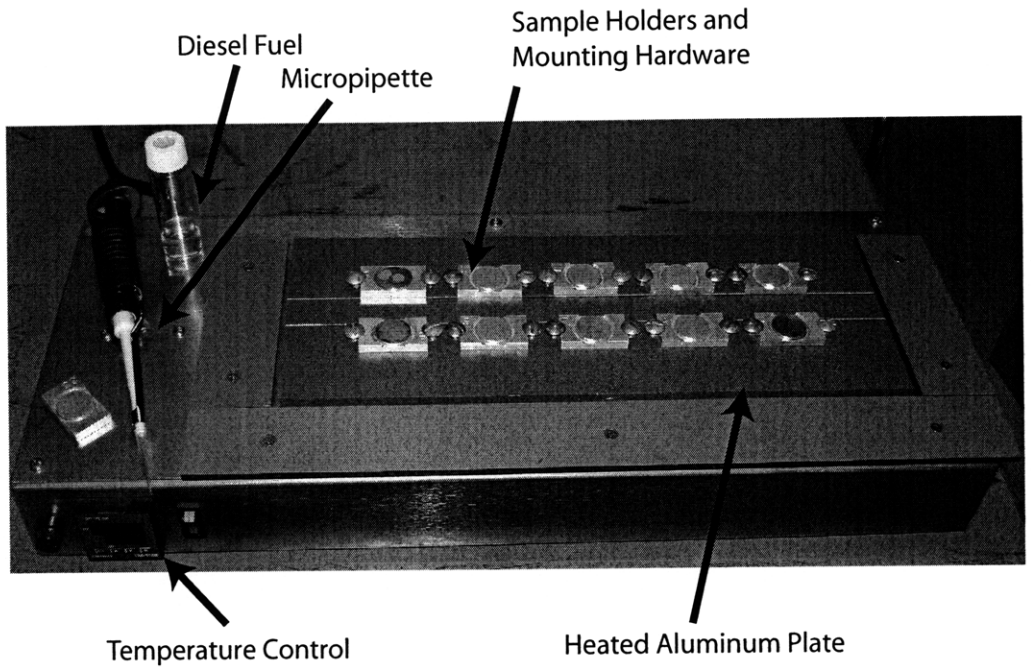


Figure 2-1: Thin Film Reactor test setup. Array of 10 sample holders allows multiple fuel types to be tested at once. Mounting hardware increases contact force between sample holders and modified hot plate to ensure good heat transfer. Fuel is metered onto the holders with a micropipette. Deposits are rinsed with hexane and weighed on a microballance with $0.1mg$ resolution (microballance not shown).

Sample Holders

Diesel fuel has a high surface energy, and furthermore this surface energy varies with temperature. Since a film of uniform thickness and known volume was desired, this

offered a challenge to design a sample holder which could constrain the diesel fuel film to a particular shape regardless of the fluid temperature. Initially the sample holders consisted of a small rectangular aluminum block with a circular pocket in the top surface. This failed to constrain the surface area and thickness of the fuel as nearly all the fuel wetted into the corners of the pocket. A second sample holder was developed in order to constrain the fluid at a knife edge rather than at a wall. This sample holder consisted of a similar aluminum block, but with a pedestal rather than a pocket in the center. The improvement to the design is shown in Figure 2-2 Before use the sample holder was lapped to sharpen the edges of the pedestal to better constrain the fluid.

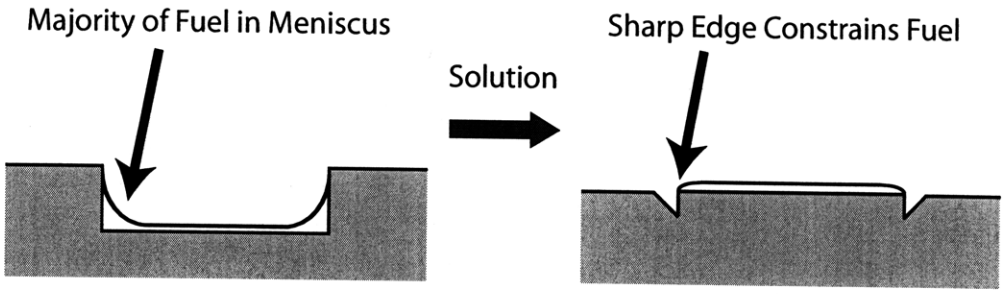


Figure 2-2: Sample Holder Design. Original sample holders did not control film thickness since the meniscus contained most of the fuel. The sharp edge of the pedestal on the advanced holders constrained the fuel since surface energy was insufficient to flow over the edge. Surface curvature of the fuel at this edge is minimal and the film thickness is approximated as the volume of the of fuel divided by the surface area of the pedestal.

Chapter 3

Results and Discussion

The thin fuel film reactor was used to conduct several deposit formation tests. The first of these tests looked at the temperature dependence of deposit formation from fully evaporated film. It was found that the weight fraction of deposit to initial fuel did not vary significantly over the range of temperatures tested. A second test was conducted to measure the rate of formation of deposit during a hot-soak period. This test attempted to model the washing away of partially oxidized fuel by rinsing off any liquid fuel remaining after a specified hot-soak period. The deposit yield was found to vary over the hot-soak cycle. During these tests it was also noticed that the surface finish of the sample holders had a significant effect on the mass of the deposits. Higher surface roughness on the sample holder resulted in formation of more deposit. In addition to these quantitative tests, several interesting qualitative behaviors of deposit formation were noted during testing.

3.1 Rates of Deposit Formation

Deposit formation rates were measured for heating of a $490\mu m$ thick fuel film at 135 °C. This temperature was chosen because the fuel did not evaporate very quickly so that the soak time could be precisely determined. At this temperature no liquid fuel remained after approximately 4 hours. In the future this test should be conducted at different temperatures and fuel film thicknesses.

Each test was conducted in a two step process. The sample holder was loaded with $200\mu l$ of fuel and heated to 135 °C and the fuel was hot-soaked for 0.5, 1, or 2 hours. The sample holder was allowed to cool then was rinsed with hexane to remove the remaining liquid fuel and any suspended deposit precursors. After the weight of the sample holder and deposit was determined, the sample holder was loaded with fresh fuel and the hot-soak cycle was repeated. Each hot-soak, rinse cycle resulted in a deposit buildup of only hundreds of μg, which was on the order of the resolution of the scale used for the experiment. Hot-soak, rinse cycles were repeated until a definite trend could be seen in the increasing mass of the deposit. The trends for the 0.5, 1, and 2 hour hot-soak cycles are shown relative to the fuel added to the sample holder in Figure 3.1.

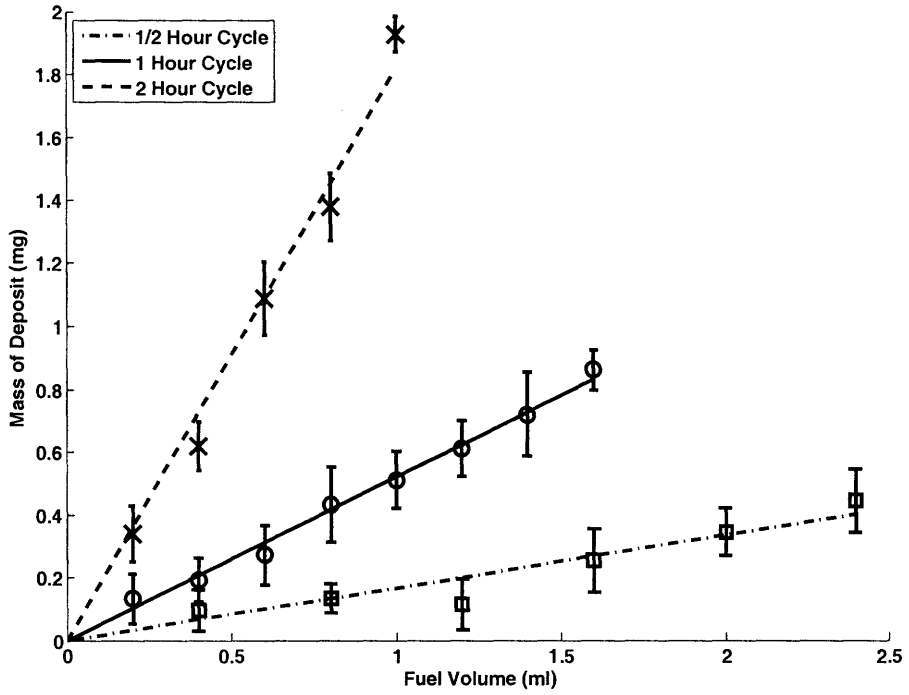


Figure 3-1: Deposit Buildup vs. Fuel Added to Sample Holder at 135 °C for Three Hot-Soak Periods. After each hot soak period the remaining liquid fuel and suspended deposit precursors were rinsed from the sample holder with hexane, $200\mu l$ of fresh fuel were then placed on the sample holder and the hot-soak cycle was repeated. As expected, longer soak times resulted in more extensive deposit buildup. 95% confidence intervals are shown for measurement of the deposit weight.

The increase in deposit formation for longer hot-soak periods shown in Figure 3.1 are not surprising. This only shows that the deposits continue to form as the fuel

remains on the heated surface. However, the primarily linear growth of the deposit as the hot-soak, rinse cycles are repeated does suggest that the substrate material does not play a significant role in the formation of the deposit as the surface is covered with deposit after the first few hot-soak, rinse cycles.

Further insight can be gained by plotting the deposit buildup against the cumulative hot-soak time as shown in Figure 3.1. The rate of deposit buildup increases with single cycle hot-soak time, even though the fuel addition rate is greater for the shorter single cycle hot-soak. As the volume of liquid fuel becomes smaller, the concentration of precursors will increase more rapidly as the fuel evaporates. If the mechanism of deposit buildup is limited by the concentration of precursors in the fluid, as suggested by the MIT model, the rate of deposit formation will increase.

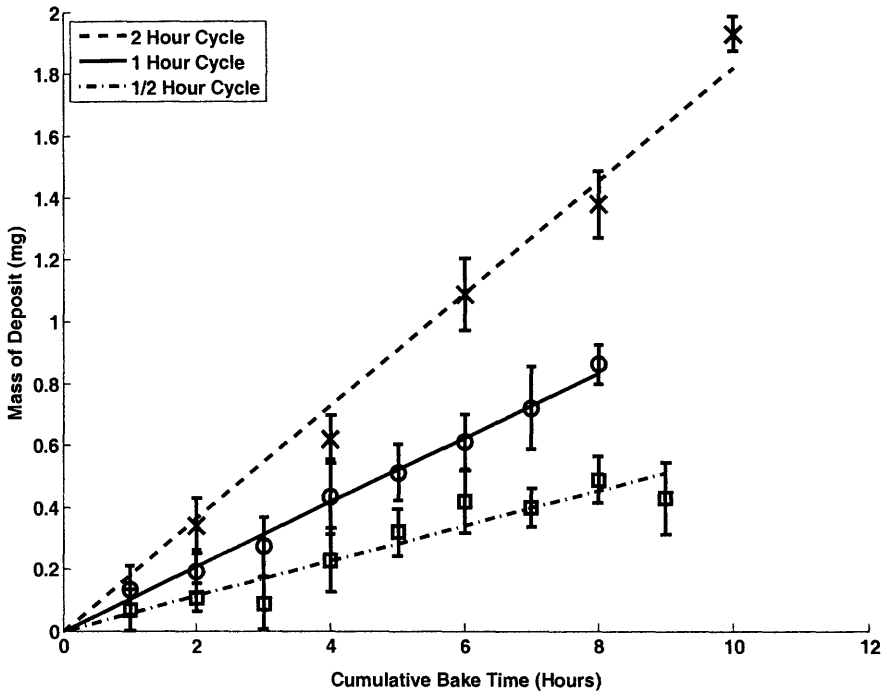


Figure 3-2: Deposit Weight vs. Cumulative Hot-Soak Time for various single cycle hot-soak times, error bars shown for a 95% confidence interval. The rate of deposit buildup increases with single cycle hot-soak time, even though the fuel addition rate is greater for the shorter single cycle hot-soak. After each single cycle hot-soak the remaining unevaporated fuel was washed away with hexane and $200\mu l$ of fresh fuel was added.

A simplified model was constructed to describe the increasing rate of deposit formation over the course of the hot-soak cycle. This model assumes the rate of fuel

oxidation to form precursors is constant, though in reality thesis rate is depend on many factors such as the oxygen diffusion rate in the fuel. The evaporation rate is also assumed constant. Based on research of fuel film evaporation by French et. al. [5] this would be a good assumption for a single component fuel. Since the diesel fuel is composed of hydrocarbons of verying molecular weight, the rate of evaporation likely decreases to some degree as the concentration of low molecular weight hydrocarbon remaining in the fuel increases. Since the fuel film is thin, and the surface area does not change significantly over the course of the hot-soak cycle, these constant rate assumptions may be a close enough approximation to gain some insight. Another simplifying assumption used in the model is that the rate of formation of the deposit is proportional to the concentration of precursors in the fuel. Finally, the density of the fuel was assumed to be constant over the course of the hot-soak cycle. After making these assumptions, the equations governing the evolution of deposit mass are given in the following:

The fuel mass (per unit area) M changes over time as fuel evaporates at the constant evaporation rate E and fuel turns to deposits of mass D:

$$\frac{dM}{dt} = -E - \frac{dD}{dt} \tag{3.1}$$

Integrating, the time dependent mass is written as a function of E, D, and the initial mass M_0:

$$M(t) = M_0 - Et - D \tag{3.2}$$

Similarly, the mass of the deposit precursors in the fuel P can be written in terms of D and the constant precursor formation rate R. Precursors begin to form at time $t = 0$ so there is no initial precursor mass:

$$P(t) = Rt - D \tag{3.3}$$

Assuming the deposit formation kinetics are dependent only on the concentration of precursors, the rate of deposit formation can be written in terms of the molar

concentration of deposit precursors and a reaction rate constant. However, since the reaction is assumed to be first order, the reaction rate can also be written in terms of the mass fraction of deposit precursors in the fuel if the molar masses are incorporated into the rate constant K:

$$\frac{dD}{dt} = K\frac{P}{M} = \frac{K(Rt - D)}{M_0 - Et - D} \tag{3.4}$$

This equation has no explicit solution in this form. Since the mass of deposit formed during experimentation was less than one percent of the initial fuel mass, a reasonable approximation can be made by considering only the initial mass and evaporation to determine the mass of the remaining fuel. Removing D from the estimate for $M(t)$ produces the following solvable differential equation:

$$\frac{dD}{dt} = \frac{K(Rt - D)}{M_0 - Et} \tag{3.5}$$

This equation can be analytically solved for D, giving the following relation:

$$D = \left(\frac{R}{E - K}\right)\left(M_0 - Kt - M_0^{\left(1-\frac{K}{E}\right)}(M_0 - Et)^{\frac{K}{E}}\right) \tag{3.6}$$

For the experiment shown in Figure 3.1, the initial weight of the fuel is about $39.0 mg/cm^2$ (assuming density of $800 mg/ml$). The evaporation rate is estimated at $10 mg/cm^2 hr$ by dividing the weight by the total drying time, which is roughly 4 hours for a $490 \mu m$ thick fuel film at 135 °C. The rate of precursor formation was estimated to be $.07 mg/cm^2 hr$ by assuming all precursors eventually end up in the dry deposit. The only variable for which an estimate cannot be made based on measurable parameters is the rate constant K of the deposit formation. Figure 3-3 shows this model fit to the recorded data. K was determined to be $30.0 mg/cm^2 hr$ for this fit. The high level of correlation between the deposit formation predicted by the model and the experimental data points suggests that the three factors used to build the simplified model, evaporation, oxidation, and condensation of the deposits, are likely to be some of the most important factors in the deposit formation process. However, a solid conclusion about the model cannot be made without more experimental data points

to compare to. The model is presented here primarily to serve as a guide to further experimentation and as a potentially useful starting point for further development of a more in depth deposit formation model.

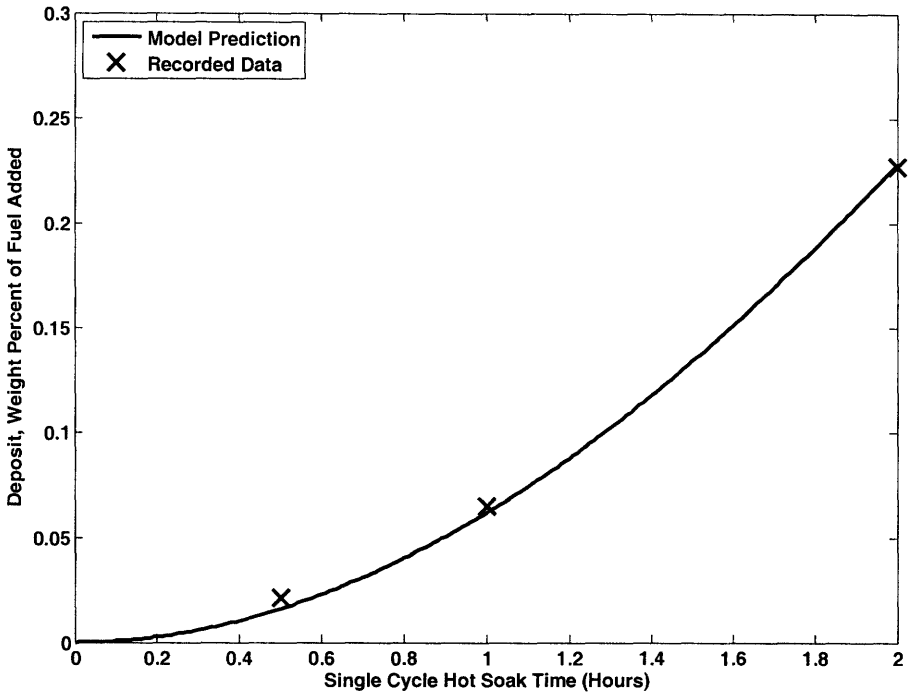


Figure 3-3: Deposit Buildup vs. Single Cycle Hot-Soak Time for $490\mu m$ films at 135 °C. The curve fit to the data is based on the simplified model shown in Equation 3.6. Only the unknown rate constant K for the precursor condensation reaction is allowed to very in the fit. All other variables were approximated from results found during experimentation.

3.2 Temperature Dependence of Dry Deposit Formation

The rate of evaporation of the diesel fuel increases significantly with temperature. A $490\mu m$ thick film of diesel fuel at 135 °C, for example, is fully dry after about 3 hours, while the same $490\mu m$ thick film will fully dry in roughly 20 minutes at 200 °C. The cumulative deposit formed by the films at 135 °C and 200 °C is nearly the same with respect to fuel added as shown in Figure 3-4.

Investigation of this phenomenon was limited to the two tests shown here. If this

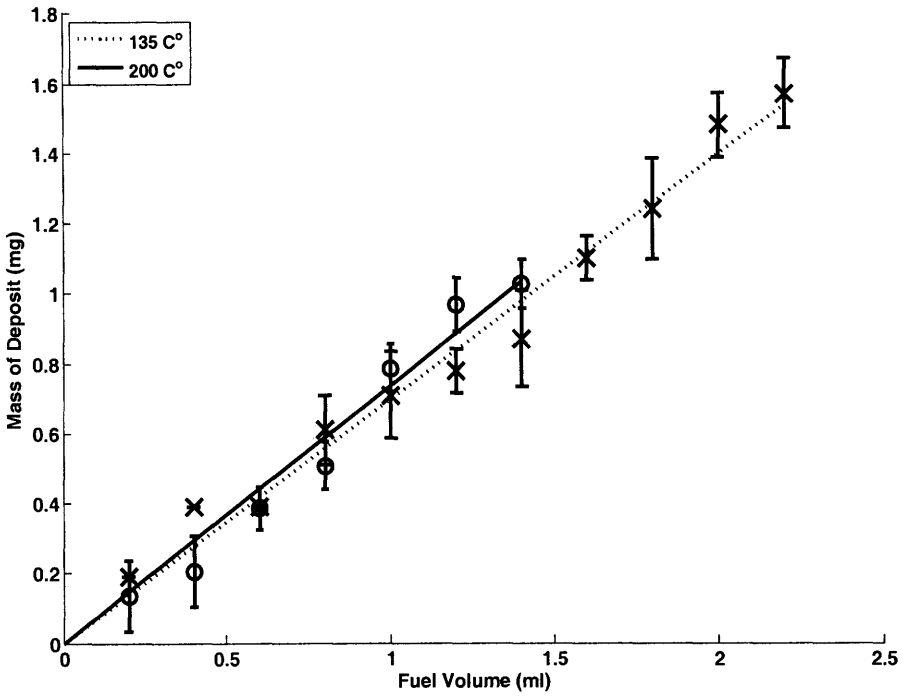


Figure 3-4: Deposit Mass vs. Fuel Added for Fully Dried Deposits. Fuel was added to the sample holders and hot-soaked until no liquid fuel remained. The sample holder was weighted and reloaded with $200\mu l$ after each hot-soak drying cycle. (note: holders were lapped with 1200 grit compound)

phenomenon can be shown to hold over a wide temperature range, the implications for testing could be significant. It is possible that slow, low temperature tests could be used to investigate behavior that is difficult to capture in faster tests. Likewise, a screening test for diesel fuel detergency could potentially be conducted at higher temperatures than expected during operation in order to decrease the cycle time of the test. Further testing should be conducted to verify the preliminary results of this test.

3.3 Surface Roughness Effects

Surface roughness was not believed to be a significant factor in deposit buildup rate and in preliminary testing this parameter was not tightly controlled. However, during the preliminary testing, deposits were observed to form more rapidly in areas of higher surface roughness. The effect was measured by conducting experiments at similar

temperatures and fuel film thicknesses but with verying surface roughness. Figure 3-5 shows the difference in deposit rate between sample holders lapped with 600 grit compound and with 1200 grit compound.

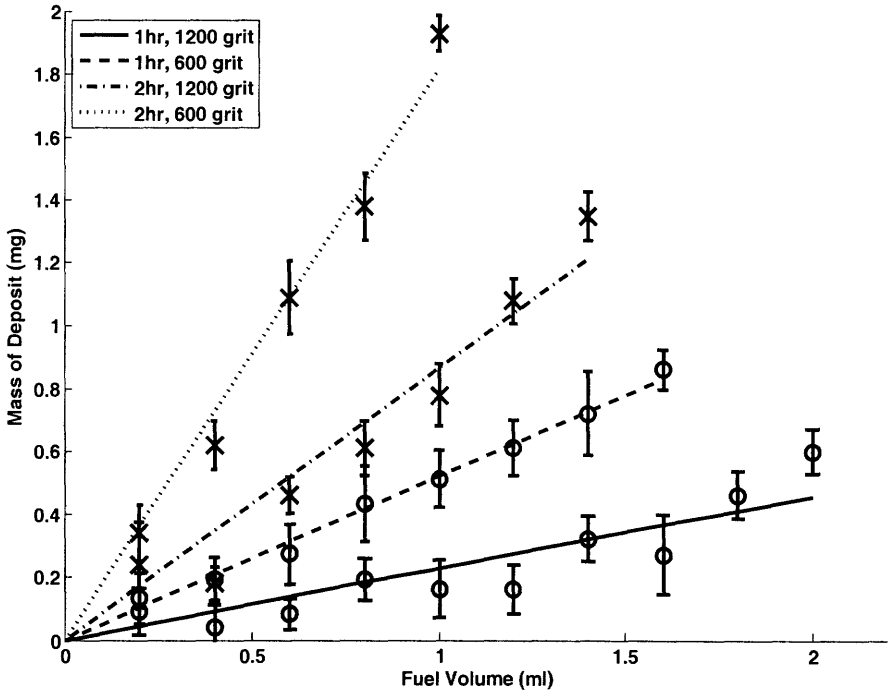


Figure 3-5: Deposit Buildup vs. Fuel Added for Varying Roughness. Sample holders were lapped with either 600 or 1200 grit lapping compound, the deposit buildup rate was higher for the sample holders with a higher surface roughness (those lapped with 600 grit compound). Temperature was held at 135 °C and film thickness was held at $490\mu m$.

These variations in deposit formation rate with surface roughness are difficult to explain. Its unlikely that the surface is acting as a catalyst as the buildup rate remains nearly linear even after the surface has been coated with a layer of deposit. It also seems unlikely that the increased rate is due to some sort of nucleation phenomenon since that again would be expected to change as the deposit coats the surface. One possibility is that the surface roughness has some effect on fuel flow at the surface of the sample holder as the hot-soak cycle progresses. Variation in surface flow is also believed to be responsible for the increased deposit formation at the edge of the sample holder.

After the results shown in Figure 3-5 were acquired, better care being taken to

control surface roughness in other tests. No further testing was conducted to better understand the mechanisms responsible for the increase in deposit formation rate from this source. Future testing is needed to develop an understanding of this phenomenon.

3.4 Further Research Opportunities

In addition to further development of theories and further investigation of the topics noted above, there were two interesting phenomenon noted during testing into which further investigation may be worthwhile. The first of these, higher deposit buildup around the edge of the sample holder, is shown in Figure 3-6. The effect may be a result of evaporation induced fluid flow towards the edge of the sample holder to which the edge of the liquid fuel is fixed. Similar effects have been noticed in drying puddles of coffee.

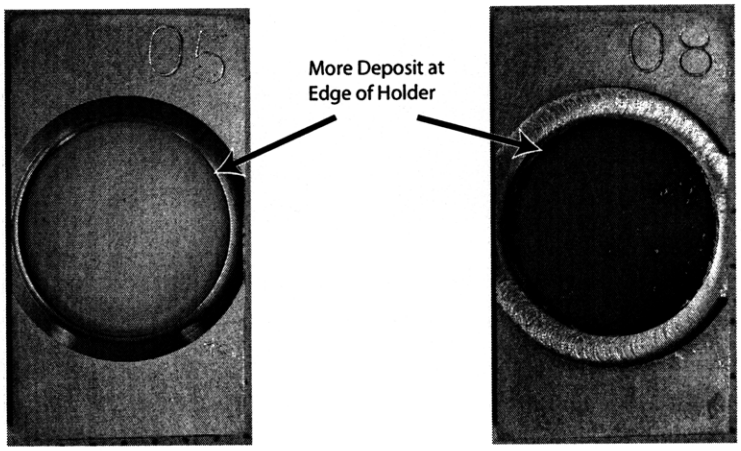


Figure 3-6: Deposit forms faster around the edges of the sample holder.

The second interesting phenomenon is related to the washing effect expected to occur during subsequent injections of diesel fuel. The tests conducted to determine deposit formation rate were cooled then rinsed with hexane to remove any remaining liquid fuel. The deposits were not soluble in the hexane so only the remaining liquid component was washed away. However, some deposits remain soluble in heated fuel. The sample shown in Figure 3-7 was partially dissolved by both low sulfur diesel fuel and by B-100 at 200 °C. If the deposit is hot-soaked for several hours after it has dried, it becomes insoluble in the heated fuels.

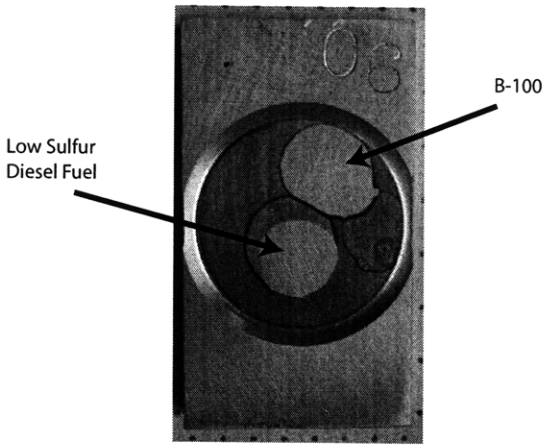


Figure 3-7: Deposits remain soluble for some time in heated fuel. The deposit shown was formed from low sulfur diesel, and were dissolved with both low sulfur diesel and B-100 at 200 °C. After dissolving the fuel the diesel and B-100 were rinsed off the sample with hexane. If hot-soaked for several hours after drying, the deposits can no longer be dissolved in the fuel.

Chapter 4

Conclusions

As efficiency and emissions standards for diesel vehicles continue to increase, the need more specialized fuel injectors will continue to grow. Nozzle size in these injectors is decreasing to better control fuel flow and increase efficiency. Current nozzle diameter is in the 150-200μm range As the nozzle diameters continue to decrease, the formation of deposits inside the injector nozzles has had an increasingly large impact on vehicle performance. Fuel detergents are used to reduce the rate of deposit buildup, but must be continually improved to keep up with the decreasing injector nozzle sizes. Currently the mechanisms responsible for deposit buildup are not well understood, and development of new fuel detergents relies primarily on empirical results from expensive engine testing procedures. This thesis looked to a thin fuel film reactor to gain insight into the deposit formation mechanisms, and also assessed the possibility of using a thin film fuel reactor as a screen test for new fuel detergents.

While no specific thin fuel film reactor screen testing method was developed, several properties of the thin fuel film formulation were found that could prove very useful for differentiating between fuel detergency in the future. It was found that when fuel was heated until it had fully dried, the temperature use to heat the sample had little effect on the total mass of the deposit produced. If this phenomenon holds true over a significant temperature range, testing could be done at high temperatures to decrease the cycle time of the test, while still being relevant to lower temperature effects in the engine. A finding that dry deposits are soluble in hot fuel immediately following

drying, but eventually become insoluble if the hot soak continues, could potentially be used to design a test based on the hot-soak time or temperature dependence on solubility.

A simple math model was constructed based on constant rate evaporation, constant rate oxidation, and first order rate for deposit precursor condensation rate. Although the model matched the experimental results well, it is likely too simplified to make accurate predictions no testing data is available. However, the model does suggest that the three parameters chosen to describe the behavior are largely sufficient to describe the mechanism. The model also provides a good point to work from for design of further testing and development of a more complete deposit formation model.

Bibliography

[1] A. Birgel, N. Ladommatos, P. Aleiferis, S. Zülch, N. Milovanovic, V. Lafon, A. Orlovic, P. Lacey, and P. Richards. Deposit Formation in the Holes of Diesel Injector Nozzles: A Critical Review. *SAE Technical Paper*, 2008-01-2383, 2008.

[2] Rinaldo Caprotti, Angela Breakspear, Olaf Graupner, and Thomas Klaua. Detergency Requirements of Future Diesel Injection Systems. *SAE Technical Paper*, 2005-01-3901, 2005.

[3] Rinaldo Caprotti, Angela Breakspear, Olaf Graupner, Thomas Klaua, and Oliver Kohnen. Diesel Injector Deposits Potential in Future Fueling Systems. *SAE Technical Paper*, 2006-01-3359, 2006.

[4] Rinaldo Caprotti, Suzuki Takaharu, and Dairaku Masahiro. Impact of Diesel Fuel Additives on Vehicle Performance. *SAE Technical Paper*, 2008-01-1600, 2008.

[5] William French, Derek Rose, Peter Kelly-Zion, and Christopher Pursell. *SAE Technical Paper*, 2008-01-2443, 2008.

[6] Marcel Gutman, Leonid Tartakovsky, Yoseph Kirzhner, and Yoram Zvirin. Development of a Screening Test for Evaluating Detergent/Dispersant Additives to Diesel Fuels. *SAE Technical Paper*, 961184, 1996.

[7] Masao Kinoshita, Akinori Saito, Souichi Matsushita, Hitoshi Shibata, and Yutaka Niwa. Study of Deposit Formation Mechanism on Gasoline Injection Nozzle. *JSAE Review*, 19:351–371, 1998.

[8] Angela Leedham, Rinaldo Caprotti, Olaf Graupner, and Thomas Klaua. Impact of Fuel Additives on Diesel Injector Deposits. *SAE Technical Paper*, 2004-01-2935, 2004.

[9] Philip P. Mulard and Philip N. China. Development of a Diesel Fuel Screening Test for Injector Nozzle Coking. *SAE Technical Paper*, 922184, 1992.

[10] R. Venkataraman and S. Eser. Characterization of Solid Deposits from Thermal-Oxidative Degradation of Jet Fuel. *Int. J. Oil, Gas and Coal Technology*, 1:126–137, 2008.

[11] Rob Williams. Development of a nozzle fouling test for additive rating in heavy duty di diesel engines. *SAE Technical Paper*, 2002-01-2721, 2002.